

CHAPTER 3

Emerging Technologies in Marine Aquaculture

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Chapter 3 looks at a spectrum of technologies from which offshore aquaculture will draw as it develops over the next 20 years. First it reviews advances in the three principal disciplines of engineering, and follows this with similar analyses of six key areas of science. The chapter ends with an examination of the forces that drive the human food supply chain, in general, and speculates on how marine aquaculture might respond to them in future decades.

Introduction

All farming, be it on land or in water, draws from an amazingly wide range of engineering and science disciplines in order to deliver wholesome food to the end consumer (Table 3.1). Farming is a synthesis of all that is known at a point in time about the animals and plants that humans cultivate and process into products that meet consumers' needs. Cultivation of living things tests man's grasp of biological, physical, and environmental science in a way that few other activities do. So it is reasonable to expect that advances in all of these disciplines in the years ahead will apply also to aquaculture, or the cultivation of living things in water. Advances will lead to improvements in efficiency and even to achievement of hitherto unattainable goals. What follows is a discussion of these disciplines and the significance that technological developments within them could render for open-ocean aquaculture in the future.

Marine Engineering

Working offshore is something for which man is ill-adapted. To do so, it is necessary to provide boats equipped with a variety of specialized equipment or to provide air-breathing humans the means to operate under water. Working offshore is therefore expensive and inherently dangerous. But advances in marine engineering in recent years have greatly increased the range of things that can be done at sea and promise even more. It would probably not be overstating the case to say that without such advances, offshore aquaculture would not be possible.

Resources from three engineering disciplines must combine to provide the platform from which offshore farmers can operate. Offshore containment systems depend upon suitable structural design and choice of materials. Operations offshore depend upon adequate mechanization of key tasks to minimize the amount of time people must spend in an inherently hostile environment. And there is a need for continuous monitoring of key environmental conditions and livestock behavior to assure optimum efficiency and livestock health.

Table 3.1. Engineering and science applications in aquaculture.

Engineering	a) Structures and materials	Containment systems Mooring Nets, ropes and lines
	b) Mechanical	General mechanization Underwater operations Feed storage, handling and distribution Net cleaning and anti fouling Fish handling and grading Product processing
	c) Electronics	Monitoring Remote control Security
Science	a) Environmental sciences	Site characterization Weather and ocean state forecasting Monitoring methods Beneficial waste assimilation (polyculture)
	b) General culture biology	New species research and evaluation Broodstock and egg supply Larval rearing Grow-out to harvest
	c) Nutrition	Definition of nutritional requirements Raw material processing Feed formulation Feed manufacture New raw materials
	d) Health management	Diagnosis Vaccines Medications and chemotherapeutics Probiotics
	e) Genetics	Selective breeding Hybridization Polyploidy Gene transfer
	f) Food science	Mechanized processing Packaging Improved shelf stability Byproduct utilization

Structures and Materials

Containment of livestock is as fundamental to aquaculture as it is to agriculture. Today, most marine aquaculture takes place in protected coastal areas, where benign conditions make it possible for man to provide containment with the structures and materials presently available. But farming in open-sea conditions presents a greater challenge, and there are now numerous research programs in progress, prototypes under test, and early commercial applications under evaluation that promise progress.

Designs of open-sea containment structures must achieve utility at an acceptable cost. Depending on the specific location (see Environmental Sciences section, following), some present designs employ a floating collar that is flexible or strong enough to withstand rough sea conditions and from which a containment net is hung (see pictures 1, 3, 10 in Figure 3.A1). Other structures are designed to avoid heavy seas by being partly or fully submerged, either permanently or as an avoidance procedure (see pictures 4, 6, 8, and 9 in Figure 3.A1; see also Loverich and Forster, 2000). Materials employed include steel, aluminum, PEH plastic, rubber, and a variety of synthetic materials used in various netting and rope products. The latter include Spectra® and Dyneema® high performance polyethylene fibers that are claimed to be fifteen times stronger than steel on an equivalent weight basis and are used, for example, in Ocean Spar Technology's SeaStation® cage (see picture 8 in Figure 3.A1).

Perhaps the biggest debate in the offshore aquaculture community, presently, centers on the utility and accessibility of surface containment structures that must then be able to survive heavy seas, versus the elegant solution that submergence provides to the problems of surface disturbance, albeit at the expense of more difficult access. It is a debate that is likely to continue for years with a variety of hybrid solutions being proposed and with recognition of the idea that no single design is likely to be right in all circumstances. However, it does seem likely that with the development of ever-more elegant techniques for monitoring and operating offshore systems remotely (see Electronics section), submerged containment methods will eventually dominate the market.

In either case, design is also driven by the necessity to assure that livestock are contained securely and that would-be predators are deterred. Already, designers have a considerable range of quite adequate materials from which to choose, and new fibers (referenced above), new methods of making them into netting, and new combinations of materials—such as plastic coated steel—promise to provide even greater reliability at comparable or lower cost. There is no obvious barrier to the development of ever-more effective containment systems, and with efforts ongoing in several parts of the world, such development is expected to keep pace with or lead the development of the industry itself.

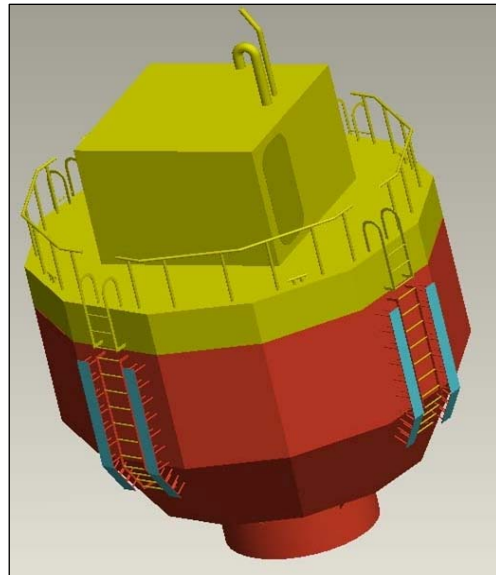
Mechanization

All farming requires that the stock are tended and handled at one time or another. Procedures for growing fish, shellfish or seaweeds differ substantially, but they all require initial seeding or stocking of the crop and, sometimes, thinning of individual plants or animals as they grow. All three must also be harvested eventually by removing them from the water and bringing them ashore for processing. Farm production of fish also requires that they be fed, that

any fish that die are removed quickly, and that they can be corralled for bath treatment of possible parasite infestations.

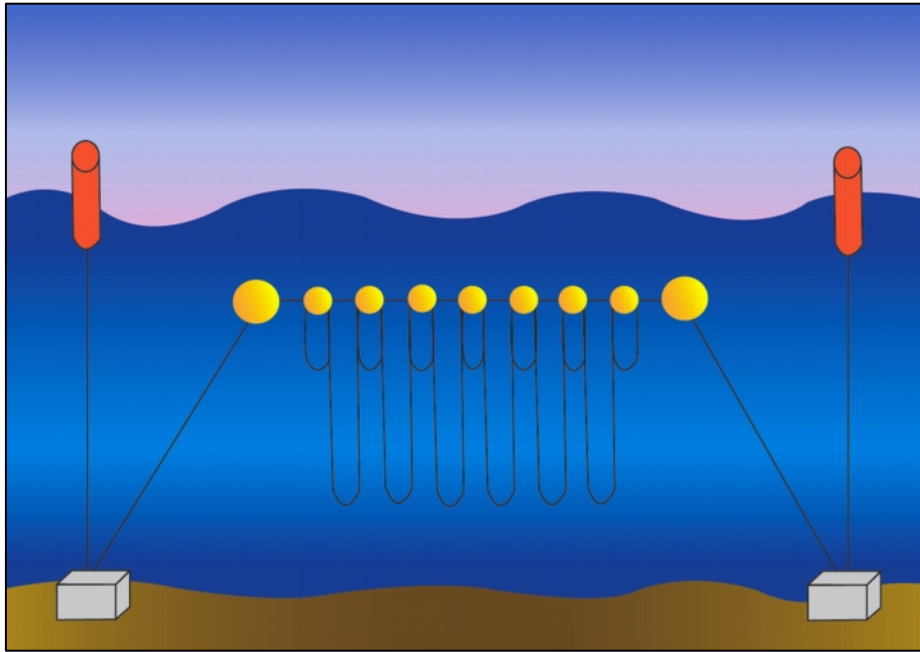
Since offshore farming is still in its early stages of development, mechanization of these procedures is still mostly experimental or relies upon adapting practices and equipment from near-shore farming. Thus, for example, the University of New Hampshire (UNH) is presently developing a feeding buoy for holding and dispensing feed offshore (Figure 3.1). Fish crowding or corraling methods under consideration would use inflatable structures within the containment systems to direct fish to a certain section of the structure so they could be harvested or moved to another container. And methods for the mechanical handling, harvesting, and seeding of rope-grown mussels are being adapted from methods presently being used near shore (Figure 3.2).

Figure 3.1. Prototype offshore fish feeder and drawing of 20-ton commercial design.



Source: University of New Hampshire Atlantic Marine Aquaculture Center

Figure 3.2. Schematic of offshore longline mussel culture.



Source: University of New Hampshire Atlantic Marine Aquaculture Center

It is neither necessary nor possible to envision the full breadth and range of mechanical handling systems and devices that will be developed in the years ahead. Two things seem certain however. First, large-scale offshore farming will not be possible unless all or most of the critical stock and materials handling procedures are mechanized. Second, as with all mechanical handling systems, the range of engineering tools available to inventors is as varied as the range of skills and talents of the inventors themselves. One only has to look at the range of tools and machines that have been invented for terrestrial farming to imagine what is possible.

Offshore, such machines will be operated from specially built workboats and, in some cases, may be remotely controlled, self-powered, and/or submersible. An example of the sort of device that will almost certainly be developed soon, but which is not yet available, is a remotely operated net cleaning device that will continuously track across the net panels, cleaning as it moves. Another example is a fish corralling system that will exploit specific behavioral traits of different species being grown. Everything that will be done on offshore farms in the future is susceptible to mechanization in one way or another, and there is no reason to suppose that the need for such mechanization will create a serious barrier to progress.

Electronics

Just as modern electronic and communications technology has revolutionized almost all manufacturing and agricultural processes, so too will it be integral to almost all aspects of offshore farming. Within the next decade, remote monitoring of most aspects of an offshore farming operation should be possible. Real-time video, data from chemical and physical sensors, and readings of high definition Global Positioning System (GPS) coordinates will allow operators to track all key performance parameters and to control some of them from shore-based

or ship-based offices. There are two primary challenges, however. First, though the underlying technologies are already well advanced, applying them in the harsh marine conditions that will be part and parcel of offshore farming will be demanding. In many cases, it may call for levels of robustness and reliability that will require specific adaptation. Second, in caring for livestock, constant observation is critical. Remote video offers an obvious way of doing this, but it depends upon good underwater visibility. Acoustic Doppler methods have been used as an alternative where visibility is poor, and UNH is experimenting with methods whereby individual fish are tagged with radio tags so their movement can be continuously tracked. By accurately observing the location of a few individuals in a population, it may be possible to make judgments about the population as a whole. Nor is it too remote a possibility that such tags could one day be used to monitor physiological functions as well as location, thus providing managers with real-time information about respiration rates, levels of stress hormones, and more. As with other engineering aspects of offshore farming, there are no obvious barriers to monitoring needs, while the possibilities appear to be almost limitless.

Environmental and Biological Science

Aquaculture, like agriculture, draws on numerous branches of the environmental and biological sciences to meet its needs. All of them have been subject to rapid advance in recent years and promise more in years to come. For this reason, it is a mistake to judge aquaculture based on its recent history, or to propose prescriptive solutions for its further development. For example, there has been a tendency in recent years for people to opine unfavorably on the sustainability of certain aquaculture practices, such as the feeding of feeds containing fish meal to carnivorous fish, or on concerns about the discharge of nutrients into marine waters. But since aquaculture is still a work in progress its sustainability should not just be judged on the status quo. The past 20 years have seen great progress in everything from the engineering of fish containment systems to the routine application of vaccines for the control of fish disease. The next two decades promise more. Like many businesses, aquaculture will adapt through technical advances to the selective pressures of commerce. Some of the advances that seem most likely to occur in the immediate future are discussed below.

Environmental Sciences

Environmental sciences are critical to offshore aquaculture in two ways. First, it is necessary to characterize farm locations in terms of weather, potential sea states, current profiles, and water quality, so that equipment and operating procedures can be specified appropriately. Ryan (2004) proposed a method for doing this for fish farm sites off the west coast of Ireland based on expected wave height. Four site classes were proposed, ranging from Class 1 (sheltered) with significant wave heights of <0.5 meter (m) to Class 4 (exposed) with significant wave heights of 2 to 3 m. Though this is helpful as far as it goes, it does not take into account the frequency with which such wave states occur or the expected strength of currents, which can be magnified by high winds. Equipment that might be specified to work in constant or semi-constant ocean swell, as occurs off the coast of Ireland, may be quite different from equipment needed in locations where the sea state is benign most of the time but where there are occasional, extreme storms.

This highlights a basic rule in marine fish farming; namely, it is always necessary to undertake a detailed physical characterization of a specific location before farming is contemplated. Oceanographic science provides numerous tools to help in such work, including GPS mapping methods, acoustic Doppler current profilers, satellite imagery, and a substantial body of documented oceanographic and meteorological knowledge. All of these tools can be used by fish farmers for site characterization, with the expectation that even more sensitive and sophisticated tools will become available in the future. Once in place, offshore farms can then draw on a formidable array of weather forecasting tools and reports in order to plan operations and/or an avoidance strategy if severe weather is predicted. Hurricane forecasting, for example, now provides up to five days' notice of a possible threat, providing sufficient time to implement contingency plans.

Next, the impact of operations on the chemistry and biology of the chosen area must be monitored. During the last 20 years, studies on the impacts of solid and soluble wastes from salmon farms in Norway, Scotland, Canada, and the United States, and from sea bass and sea bream farms in the Mediterranean, have resulted in a substantial body of knowledge (EAO, 1997; NOAA, 2001; SAMS, 2002; European Commission, in progress). The primary conclusions are that, in most cases, effects on water quality are minimal, while effects in terms of sedimentation and organic enrichment of the seabed under fish farms are directly linked to site conditions and management. In fact, it has been learned that determination of excessive build-up of sediments under fish farms is the most sensitive and reliable indicator of when "carrying capacity"¹ of the local environment may become overused. These studies also predict that carrying capacity of offshore aquaculture locations will be greater than inshore locations, due to greater water depth and stronger or more consistent currents.

Techniques and instrumentation for monitoring the biological and chemical impacts of offshore aquaculture may be expected to become more accurate and better targeted as the industry develops. All of the analytical techniques originate in other branches of research; their appropriate and targeted application is key to designing monitoring programs that yield useful information at a reasonable cost. As knowledge increases, remote, continuous monitoring of some key parameters may become possible, with data being uploaded to websites for review by the public and/or regulatory agencies.

Environmental concerns about shellfish farms are less, since no feed needs to be provided for the stock. Instead, creatures such as mussels and scallops obtain their food by filtering microscopic plants from the water in which they live. However, the potential to over-graze a body of water exists if too many shellfish are held in one place, and accumulation of shell and other biological material from organisms that colonize the farm structures can occur on the seabed. Farming of seaweeds presents even less concern, because these plants require only sunlight and nutrients drawn from the surrounding water to grow. In fact, when grown in combination with finfish, seaweeds might be used to recover or recycle some of the wastes those fish produce.

¹ Carrying capacity is used in this context to denote the capacity of a given body of water to assimilate waste products from aquaculture facilities without significant adverse effects.

This introduces the idea of what is known in agriculture as integrated farming. Sometimes it is called “polyculture,” and it refers to the culture of more than one organism, each one of which—by feeding at a different trophic level—helps to maximize the efficiency with which nutrient inputs to the system are used (Chopin, 2005). Such multiple cultivation may take place in the same container (polyculture) or it may be performed in a series of containers (integrated aquaculture). Either way, it is particularly well-suited for aquaculture, where nutrient wastes are rapidly dispersed and become immediately available to the plants that use them. In terrestrial farming, this can only be accomplished by the physical removal of wastes and subsequent spraying on fields. By contrast, aquatic plant production can utilize the confined culture of a seaweed species or the unconfined, natural enhancement of phytoplankton, which, in turn, can become food for confined bivalve shellfish. The respective merits of each are determined by crop value. This evolution of aquaculture promises to become extremely important over the long term.

General Culture Biology

Perhaps the most dramatic, or at least visible, progress in aquaculture over the last 30 years has occurred in the field of general culture biology. Advances have included the selection and domestication of new species, development of hatchery rearing methods for species that have delicate, fragile larvae with complicated life stages, and establishment of breeding stocks of important species that provide the basis for year-round production and genetic improvement. It is expected that such progress will continue. In particular, advanced hatchery and breeding techniques will be applied to an ever-widening range of species. Though many will be found not to domesticate well, some will become substantial aquatic farm species in the same way that salmon, tilapia, shrimp, mussels, and scallops have become important in the last 30 years, while others may find roles as niche market species.

From the market’s point of view, there seems to be a major opportunity for farmed, white-fleshed, marine fish that can provide comparable value to farmed salmon. Species such as cod, halibut, red drum, cobia, black cod, snapper, and some tuna have promising attributes, and they are the subjects of research and/or small-scale commercial production in several countries. Which of them might become candidates for large-scale offshore aquaculture depends on market acceptance and the costs of farming them. Simplicity in the hatchery, fast growth, responsiveness to farm conditions, and efficient growth on low-cost feeds are all attributes that lead to low-cost farming—an essential prerequisite to providing affordable seafood. Since salmon farming has proved this possible, salmon provides a good benchmark against which the potential of new species can be measured.

Nutrition

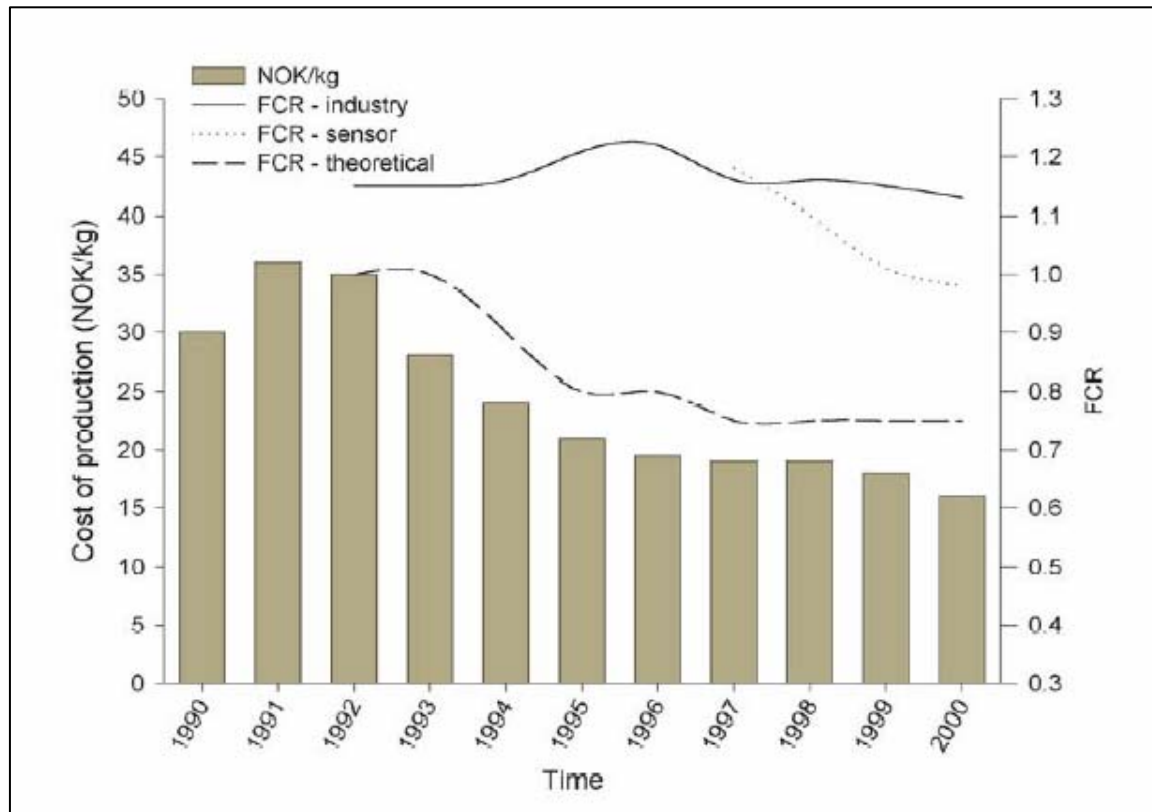
Most captive finfish must be provided with food, therefore nutritional science is another critical discipline in aquaculture. It is an area where some of the most important developments may occur in years to come, especially since fish feed researchers and manufacturers can draw upon a huge body of knowledge in terrestrial animal nutrition. As is true in the farming of chickens or pigs, the feed in fish farming can account for over 60% of total costs. Therefore, better and lower cost feeds will render a large impact on the economic competitiveness of the industry. Extensive research is already progressing in several key areas, including:

- Better definition of the nutritional requirements of different species, especially amino acid and lipid needs, since they have a direct bearing on what raw materials can be used.
- Identification of alternative raw materials that can be used to replace fish meal and fish oil in feeds. These may be processed wastes from other industries, such as meals made from chicken processing waste or fermentation byproducts. Or, they may be agricultural raw materials such as soybean (United Soybean Board, undated) and canola, which may themselves be genetically improved to increase nutritional value to target species. This is discussed in more detail in Chapter 6.
- Processing of raw materials to make them suitable for fish. Some potentially suitable plant materials, such as soybean, contain anti-nutritional components that must be denatured by cooking or other treatment prior to their use in fish feeds.
- Formulation of feeds so that nutritional requirements of target species are more completely met. This is especially important for brood fish, in which egg quality can be compromised by inadequate nutrition, and in fish that through genetic improvement grow very quickly—thereby imposing extra nutritional demands.
- Milling of raw materials into water-stable rations that are appetizing to fish. Usually this requires some form of pelleting; for example, cooking extrusion, which produces water-stable feed pellets to which high levels of fat can be added. Extruded feeds have become widely used for many species in recent years, especially for salmon, and have contributed greatly to improvements in feeding efficiency.
- Better definition and control of feeding practices that optimize feed intake and minimize waste.

The success of this research will be measured mostly in terms of cost per unit of weight gain by the animals in culture. Salmon farmers, for example, who have pioneered much of what is now known about net-pen aquaculture, have been able to reduce the food conversion ratio (FCR) from about 2:1 some 20 years ago to an industry average of about 1.3:1 today. This represents a substantial savings in cost and reduction in wastes discharged. Further gains will occur in the years ahead, with an anticipated theoretical minimum of about 0.7:1 to 0.8:1 (Figure 3.3).

Health Management

A basic rule of animal or plant husbandry is that maintaining a good rearing environment will minimize health problems. This idea is often thought of today in terms of general animal welfare, with the clear underlying principle that if the creatures in care are kept clean, fed well, and not overcrowded they are more likely to be healthy. As aquaculturists learn more about basic welfare for the species they grow, it is expected that health problems will be minimized. This is especially likely to be the case in the offshore environment where water quality is good and conditions more stable than inshore, and where rates of water exchange through the culture systems will be higher.

Figure 3.3. Gains and projected gains in food conversion rates (FCR) for salmon.

Source: Blyth and Dodd, 2002

However, parasitic infestations and bacterial and viral diseases are a constant threat in all forms of husbandry, making an active livestock health management plan mandatory. In aquaculture, major advances have been made over the last 30 years in techniques for diagnosing health problems and in methods of dealing with them. These include better diagnostic tools (especially for viruses), improved understanding of the immune systems of the animals in culture, development of vaccines (especially against bacterial diseases in fish), and the advent and registration of new and better chemotherapeutants. On a parallel track, regulations governing the movement and sale of live aquatic organisms have been tightened, in part at least, because disease screening techniques have improved.

One of the most dramatic areas of improvement has been in the field of fish vaccines where, again, the salmon farming industry has pioneered the way. For example, until the early 1990s, two bacterial diseases, *Vibriosis* and *Furunculosis*, constantly caused problems in farmed salmon and in some other species too. Though vaccines had been developed, they were not very effective until it was found that they should be injected into the body cavity of juvenile fish as an emulsion in vegetable oil. This discovery spurred rapid development by pharmaceutical companies, such as Alpharma and Novartis (Aquahealth), and vaccines against at least six fish diseases are in use today. The salmon farming industry in Norway, for example, now uses less than 0.5% of the medicine required to treat these diseases than it did 10 years ago (Ludvigsen, 2003). Vaccines are presently under development against common parasitic infestations and

viral diseases in several species of fish in different countries. They will provide future offshore aquaculturists with powerful new health management tools. Oral vaccines, in particular, if they can be developed, would greatly simplify and extend how vaccines are used, and in this aquaculture can draw on scientific advances elsewhere.

Genetics

Data in Watts and Kennet (1995) show how the performance of broiler chickens was improved over 60 years between 1935 and 1994 (Table 3.2) when the key production parameters of finished weight, FCR, and growth rate improved by 1.7, 2.3, and 2.5 times respectively. Improved genetics is generally considered to have contributed 80% of these advances.

Table 3.2. Improvements in broiler chicken growth rate and feed conversion rate.

Year	Weight (kg)	FCR	Age marketed (wks)
1935	1.27	4.4:1	16
1950	1.36	3.5:1	11
1975	1.70	2.0:1	8
1994	2.11	1.9:1	6.5

Source: Watts and Kennet, 1995

Arguably, aquaculture is at least 50 years behind the broiler industry, so this example provides insight into how dramatically aquaculture could advance in the years ahead. Eknath et al. (1991) showed that some improvement has been achieved in salmon already, versus species new to aquaculture - where first generation progeny are from wild stock. It is highly probable that genetic gains similar to those achieved in terrestrial animals will be possible with aquatic livestock, especially since their high fecundity allows for increased selective pressure. Also, modern genetic techniques, such as the use of genetic markers in conventional breeding programs, can be used to focus effort on specific traits.

Alternative genetic tools are available too. Triploidy, where a fertilized egg is induced by a simple temperature or pressure treatment to retain an extra set of chromosomes, is used in some species to produce non-reproductive stocks. For example, triploid rainbow trout eggs are commercially available and are used in several state recreational fishery programs because fish from them do not mature sexually and, therefore, can reach large, “trophy” sizes. Triploidy, a natural phenomenon but not self-sustaining in nature because the progeny cannot breed, is now the subject of research with several species that are of interest to aquaculture (Troutlodge Inc., undated).

Another technique that might be used to improve aquatic stocks for farming is the transfer of genes between species to create “transgenic” stock, or genetically modified organisms (GMOs) as they have become commonly known. A frequently cited aquacultural example is a genetically modified Atlantic salmon developed by a company called Aqua Bounty Technologies Inc. Due to the transfer of genes from Chinook salmon and ocean pout, this transgenic salmon produces a higher than normal amount of growth hormone and will grow four to six times faster than genetically normal salmon (Aqua Bounty, undated).

One concern about genetically improved aquaculture species and, especially, transgenic organisms is that they may become feral in the marine environment. Triploidy, and other techniques to make such improved animals non-reproductive, would mostly overcome such concerns, because the animals could not then establish a population or interbreed with wild stocks. But this is still an area where caution and further research are needed. Equally, however, GMO research is also an area that may provide huge benefits, like those it has already conferred in terrestrial crop farming, and must be given consideration in any long-term evaluation of aquaculture's potential.

Food Science

This subject embraces a wide spectrum of technologies that can be applied post harvest to assure quality and safety, to improve efficiency, and to add value to the finished product. Procedures for post harvest handling of seafood to assure best quality are well understood and there does not seem to be much scope for new technology *per se* to add materially to what is known. The key is to ensure that these procedures are always followed and a number of quality assurance programs are available to facilitate this, including the U.S. Food and Drug Administration's (FDA) Hazard Analysis and Critical Control Point (HACCP) program and the International Standards Organization (ISO) quality assurance certification programs. In general, since the harvesting process for seafood raised on farms is inherently more controlled than for wild-caught seafood, such control programs are more easily applied to aquaculture products.

Mechanization of processing procedures is a field where there is already considerable innovation but, also, opportunity for substantial efficiency improvements. This is particularly important in the United States, where the higher cost of labor makes manual processes noncompetitive with those of lower-wage economies. For example, a primary reason for the initial competitiveness of Chilean-farmed salmon fillets in the United States during the late 1990s was that the cost of doing all the work in Chile to produce a "pin bone out, skinless fillet" was much lower than in other major producing countries such as Norway and Canada (Johnson, 2003). Today, the development and application of filleting, skinning, and pin-boning machines is narrowing the competitiveness gap. The trend towards mechanized processing will continue, especially for fresh seafood products, because of the advantages in producing such products close to their market.

Consistency of supply of farm-raised products is another advantage, enabling processing plants that invest in expensive equipment to be assured of its efficient use. A notable example of such mechanization and efficiency is the U.S.-farmed catfish processing industry, where plants are able to produce a wide variety of processed, value-added catfish products despite having to do so within the high wage U.S. economy.

Improved shelf stability of seafood products is another area where technological advances will affect the competitive dynamics of the industry. Freezing, canning, salting, smoking, vacuum packing, and retort pouching are all techniques in common use today. However, they all change the product to a greater or lesser degree, and with it, the perception of quality. Fresh seafood still carries a cachet that few shelf-stabilized products can match. Several techniques are used today to extend the shelf life of fresh foods, all designed to kill or inhibit spoilage bacteria. They include ozonation of processing wash water and ice, modified

atmosphere packaging, and irradiation. The latter has been approved by the FDA for meat and poultry but not yet for seafood.

An underlying assumption, or at least one that is not often questioned, is that the market premium for fresh seafood will continue, and this will drive further developments to extend the shelf life of fresh products while constraining producers who find it difficult or expensive to supply fresh products. Presently, for example, the U.S market for fresh tilapia fillets is supplied almost exclusively from Central and South America, because airfreight is available at a reasonable cost. On the other hand, Chinese farmers, who could otherwise be extremely competitive in this market, are restricted to shipping frozen tilapia fillets because the cost of airfreight from China to the United States is prohibitive. It is easy to see how changes in market preference toward frozen seafood, or shelf-life extension of fresh products that would allow sea freight to be used, or changes in the cost of airfreight, could change competitiveness in a global market. It is expected that producers will constantly probe for advantages in this area. The competitiveness of future U.S producers, therefore, will constantly be challenged and will demand international levels of productivity and efficiency in all parts of the business.

An aspect of the seafood industry where aquaculture is not yet particularly efficient is its use of byproducts from processing. And yet, due to the consistency and predictability of supply, plants that process aquaculture products have an intrinsic advantage over those that process wild-caught products. There are a number of processing technologies in use for converting fish and shellfish waste into marketable products (Johnson, 2003). Some of these processes involve grinding and cooking of raw fish and offal, drying of raw material, or the hydrolysis of fish protein through some form of enzymatic action. Outputs from these processes include pharmaceuticals and nutraceuticals, industrial compounds, food products (oils, gelatins, flavors, and extracts), feeds, and fertilizers (Table 3.3). Some products are of sufficient value that they may, in fact, become primary targets.

The key to successful byproduct recovery is to have a consistent supply of raw material in a volume sufficient to justify investment in the processing equipment and management of the byproduct operation. Currently, most aquaculture activities are too small to meet the volume criteria, and disposal of processing waste represents a cost rather than a source of income. Realistically, this is likely to remain the case for some time to come, but clearly it represents upside potential for the industry and offers one example of the benefits that derive from larger-scale production.

Long-term Considerations

The long-term direction and future of offshore aquaculture will be governed by forces that drive the food supply chain in general. These forces include both threats and opportunities. Tables 3.4 and 3.5 summarize aspects of a future competitive environment that seem especially likely to affect the seafood industry.

Table 3.3. Seafood industry byproducts.

Industry	Product	Application
Aquafeed	Fish hydrolysates	Feed additives
Animal Feed	Co-dried products	Flavorants and attractants
Pet Feed	Fish hydrolysates Fish oils Natural pigments	Protein supplements and flavorants Fish oils Antioxidants and pigment enhancement
Organic Food Industry	Fish fertilizers	Plant nutrition
Nutraceuticals	Fish oils Peptides Chitin Chondroitin sulphate	Health promotion
Industrial Compounds	Chitin Gelatin Enzymes	Paper making Cheese processing Water purification
Human Food	Fish oils Gelatin Seafood derivatives	Health foods Kosher and Hatal gelatins Flavorants and thickeners
Pharmaceuticals	Specialty products	Drug delivery Anticoagulants Arthritis, cancer, and other treatments Photoelectric applications Biotechnology

Source: Johnson, 2003

The balance between human needs and the Earth's capacity to supply them is delicate and subject to continuous change. Human needs change in response to numbers of people, perceptions of preference, and market forces, while understanding of capacity changes in response to new technology and new appreciation of the ecological footprint that activities impose. Most animal agriculture, as it is practiced today, represents an ecological extravagance that man embraces because meat is a preferred food item and, in many cases, provides nutrients that would not be available in adequate quantities from an all-vegetable diet. Until now, it has also been an affordable extravagance, since the number of humans has been moderate and a high level of meat consumption has been confined to a relatively small proportion of them. But trends suggest that this may not be the case much longer (Figure 3.4). Since human consumption of meat is driven both by an increase in the human population and its overall level of affluence, how long will it be before resource pressures impose limits on such growth? And, what will happen when they do?

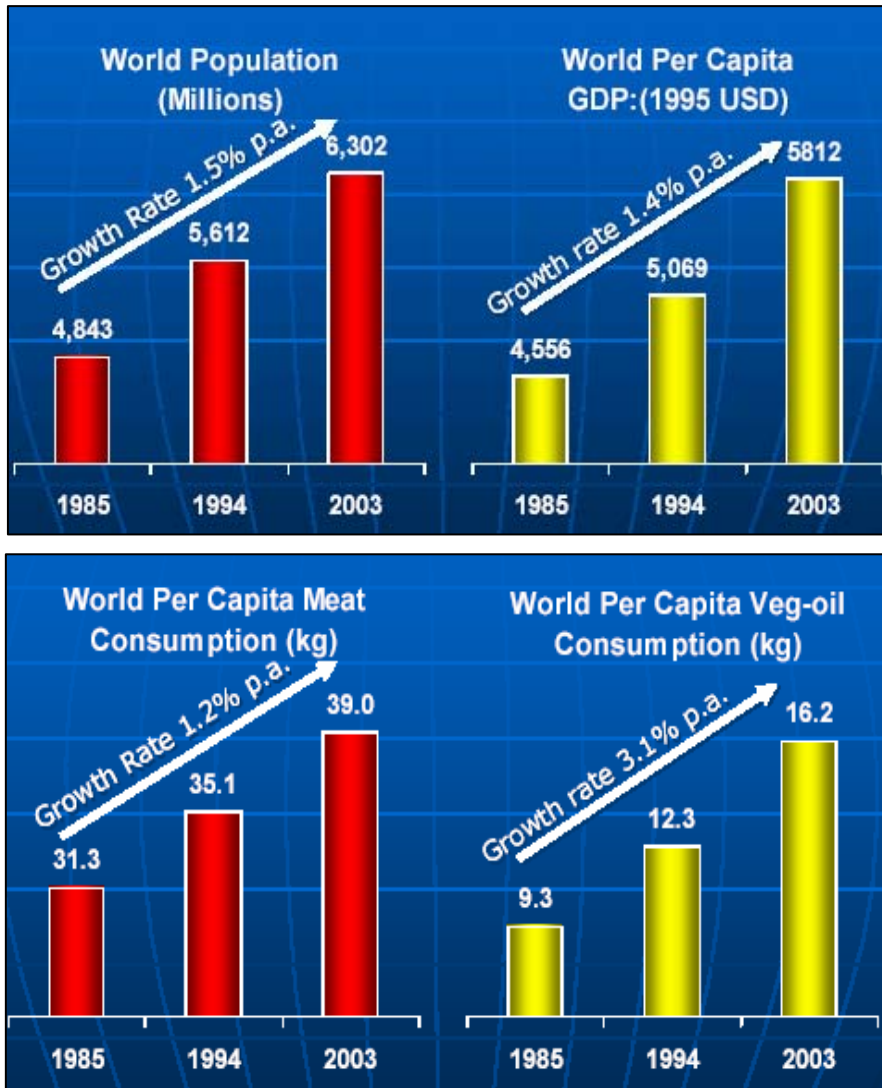
The threats (Table 3.5) are all consequences of such resource pressures or responses to them. For example, increasing acceptance of simulated meat made from textured vegetable protein is a likely response to rising costs and, therefore, prices for the real thing. Similarly, vegetarianism, or at least a reduction in per-capita consumption of meat, is another response (the Atkins diet notwithstanding), especially in the United States where levels of meat consumption at 98 kg per capita per year is 2.5 times the world average, and dietary guidelines are urging general moderation.

Table 3.4. Long-term threats and possible responses or consequences.

Threat	Impact	Response / Consequence
Higher energy costs	Will affect all parts of the business especially marine mobility	Mechanization and remote monitoring and control (see Marine Engineering section of this chapter).
Feed raw material shortages	Feed cost increase	Assuming feeds can be formulated from a variety of feed ingredients (see Chapter 4) fish farming will be no more affected by feed cost increases than other animal farming industries. In fact, it may have an advantage because some fish may use feed more efficiently than their terrestrial counterparts (Forster and Hardy, 2002).
Development of synthesized or artificial foods; e.g., artificial crab meat	Foods made from single cell proteins, textured vegetable proteins or, possibly, cultured muscle tissue could be a competitor.	Assuming such products are safe, are effective imitations, and are cost competitive, the only response can be to emphasize the benefits of “the real thing.”
Omega 3 fatty acid supplements	Weakens a key selling point for seafood, i.e. health.	There are other, though less unique, benefits of seafood that can be promoted but fish oil pills and fortified foods are already being sold. In the long term, seafood must sell because it is good tasting food not because it is “medicine.”
Vegetarianism due to concerns about animal welfare or the ecological cost of humans as carnivores	Reduced consumption of animal proteins	Animal welfare concerns may be partly addressed by good farming practices and humane slaughter methods, which are more easily demonstrated for aquaculture compared to commercial fishing. Also, the ecological costs of farmed seafood may be less than those of producing meat on land, which would give aquaculture a competitive advantage

Aquaculture offers another response. By finding ways to use a greater proportion of the Earth's surface for food production, and by growing species that may be more efficient in converting resources into animal tissue, aquaculture promises to change how the Earth's capacity is presently understood. The opportunities and possibilities identified in Table 3.5 touch upon this promise. It is impossible to know how it will actually develop. Other factors besides simple resource considerations will determine the ultimate outcome. But insofar as the future will be driven by the balance that is struck between human needs and the Earth's capacity to supply them, aquaculture in the oceans seems certain to become increasingly important.

Figure 3.4. World trends in population, gross domestic product (GDP), meat and vegetable oil consumption.



Source: Bunge, undated

Table 3.5. Long-term opportunities and possibilities.

Opportunity	Impact	Response / Consequence
Increased purchasing power in developing countries	As China, India and other Asian countries modernize, their people will seek to upgrade their diets. This will increase demand for what may be a limited supply of some products.	Though offshore aquaculture will seek to expand internationally to meet this demand, it may be difficult to keep up. Since the United States can be a competitive producer, a homeland industry can benefit from market strength and help to assure supply to U.S. consumers.
Cold-blooded creatures that do not maintain body temperature or have to resist gravity are more energy efficient than warm-blooded terrestrial animals	Less food energy will be needed by aquaculture to produce an equivalent amount of animal protein. And less carbon dioxide or methane will be produced as waste products.	In an energy-limited world, this may be a key long-term advantage for aquaculture. It remains to be thoroughly examined and quantified by detailed input/output analysis, but there are good theoretical grounds to believe it will be found to be real (Asgard et al., 1999). Moreover, a case may be made that farmed seafood provides a better nutritional return for the inputs invested than do farmed mammals and birds.
Nutrient recycling	Nutrients discharged as wastes may be taken up and used by the marine food chain more effectively than nutrients from terrestrial animals that may overload localized terrestrial capacity. More aquaculture could, therefore, lessen impacts on land, freshwater aquifers, and near-shore marine waters.	This also needs to be demonstrated but there are theoretical grounds for believing it could be true. Nutrients from offshore aquaculture will be widely dispersed quickly, thereby becoming available to phytoplankton over a large area receiving, proportionally, a much greater amount of sunlight than nutrients sprayed on fields.
Polyculture – the controlled recovery of nutrients by cultivating more than one organism	This will have the same impact as nutrient recycling above except that the “take-up” will occur by other farmed organisms that may be grown and harvested at a profit (see Environmental Sciences section of this chapter).	The most direct way to accomplish this is through the culture of seaweeds for food, chemicals or biomass. Indirect recovery is also possible by cultivating filter feeding shellfish that feed on enhanced phytoplankton stocks that will develop in the vicinity of a fish farm.
Synergy with wave and wind energy systems	More efficient use of the maritime infrastructure is needed for both industries.	Since working offshore is inherently difficult, and therefore expensive, this has the potential to reduce costs. Wave energy systems will also provide protection for aquaculture structures.

Appendix

Figure 3.A1. Open-sea cages: A design history.



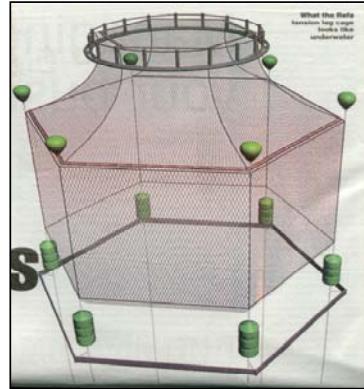
1. Bridgestone cage circa 1986. Non submersible, flexible structure. Still in use and one of the most successful open sea cages to date.



2. Viking Sea Going Farm circa 1988. Relied on strength to withstand ocean forces and failed.



3. FarmOcean semi submersible cage circa 1990. Still some in use but few were sold. Expensive



4. Refamed Tension Leg cage circa 1990. Relies only on floats and lines. Deforms in currents. Used extensively in Italy

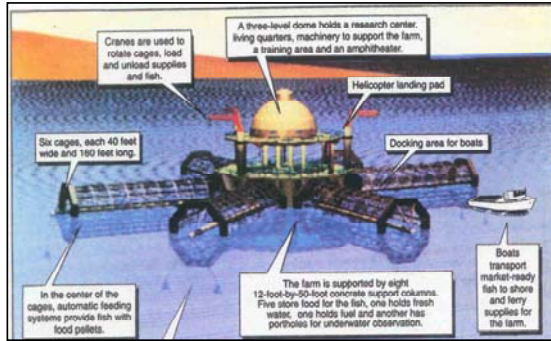


5. Ocean Spar cage circa 1990. Relies on anchor tension to hold shape. Partly submersible but has not done well in really heavy sea conditions.



6. Trident Cage circa 1992. Geodesic design, submersible but with interior single unit net. No longer made or in use.

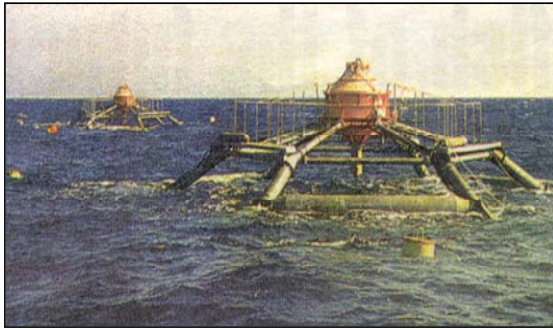
Figure 3.A1 (continued). Open-sea cages: A design history.



7. Seatrek concept cage Circa 1992. Permanently submerged barrel cages. Never built



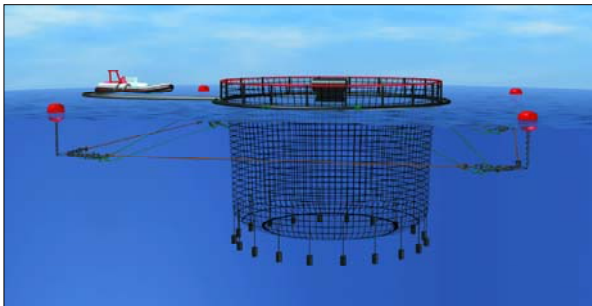
8. SeaStation single spar submersible cage, circa 1992. Fixed volume, tensioned rigging lines to support net, now in service in several countries



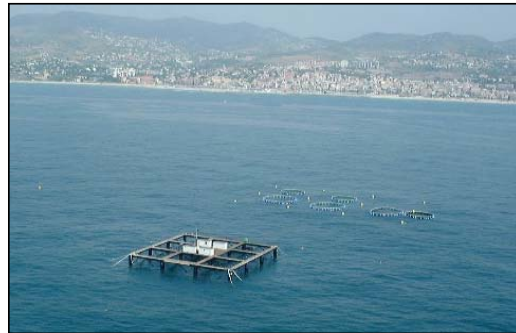
9. Sadco Shelf submersible cage, circa 1992. Similar to SeaStation but rigid structure supports net and includes integral feeder. Now in use I several countries.



10. Dunlop Tempest cage, circa 1990. Very similar to the Bridgestone cage.



11. Submersible PolaCirkel cage, circa 1994. Conventional PEH cage that can submerge when rim is flooded. Now in service in several countries

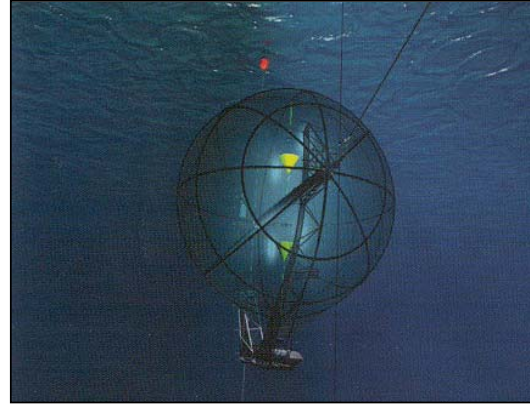


12. Platform cage, Spain, circa 2000. Uses oil field type structure fixed to sea bed for net support

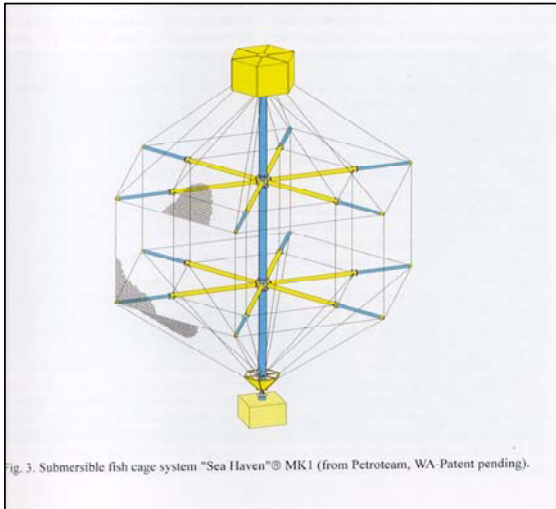
Figure 3.A1 (continued). Open-sea cages: A design history.



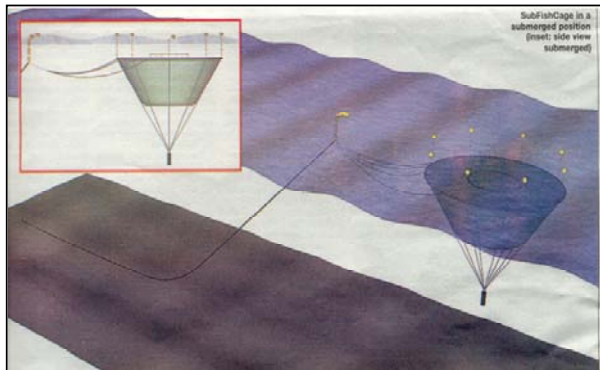
13. Ocean going concept cage , Spain , circa 2004. Specially designed for tuna where wild caught juveniles are used



14. Ocean Glob, circa 2004. Norwegian concept cage made with PEH pipe. Yet to be built and tested



15. Sea Haven cage circa 2004. Under development in Western Australia.



16. SubFishCage, Europe, circa 2004. Concept cage being designed as part of EU development project

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